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Matsuo et al.

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(54) **SOLID OXIDE FUEL CELL SYSTEM RESPONSIVE TO EXPLOSIVE VAPORIZATION OF WATER IN REFORMER TO CONTROL POWER**

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(73) Assignee: **TOTO LTD.**, Fukuoka (JP)

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H01M 8/06 (2016.01)
H01M 8/04 (2016.01)
H01M 8/12 (2016.01)

(52) **U.S. Cl.**
CPC ***H01M 8/0618*** (2013.01); ***H01M 8/0494*** (2013.01); ***H01M 8/04425*** (2013.01); ***H01M 8/04559*** (2013.01); ***H01M 8/04619*** (2013.01); *H01M 2008/1293* (2013.01); *Y02E 60/50* (2013.01); *Y02E 60/525* (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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(57) **ABSTRACT**

To provide a fuel cell system with which degradation of fuel cells can be suppressed by avoiding the ill effects caused by bumping of water used for steam reforming during the electrical generation. The present invention is a solid oxide fuel cell system including: a fuel cell module, a fuel flow regulator unit, a reformer for reforming supplied fuel, a vaporizing section for supplying steam to the reformer, a water flow regulator unit, and a controller for controlling the fuel supply device and water supply device, and for controlling the power extracted from the fuel cell module; whereby the controller is furnished with: a bumping determination circuit for determining the occurrence of excessive vaporization of water in a vaporizing chamber, and an extracted power limiting circuit for limiting the power when the bumping determination circuit has determined excessive bumping of water.

6 Claims, 12 Drawing Sheets

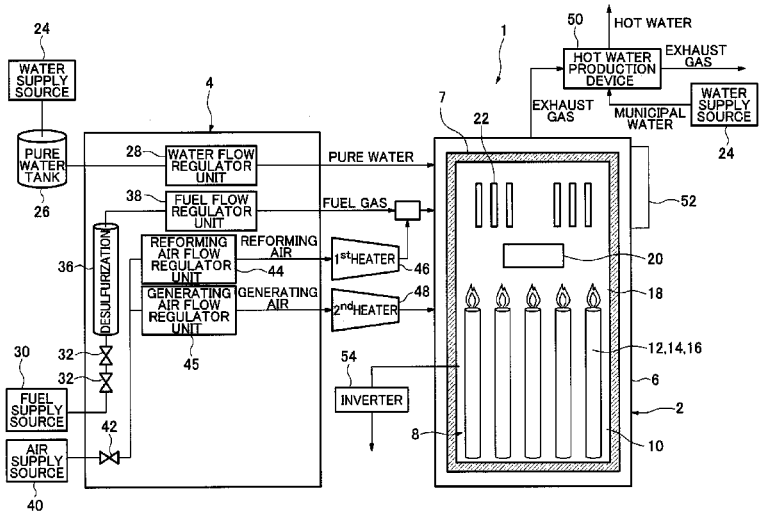
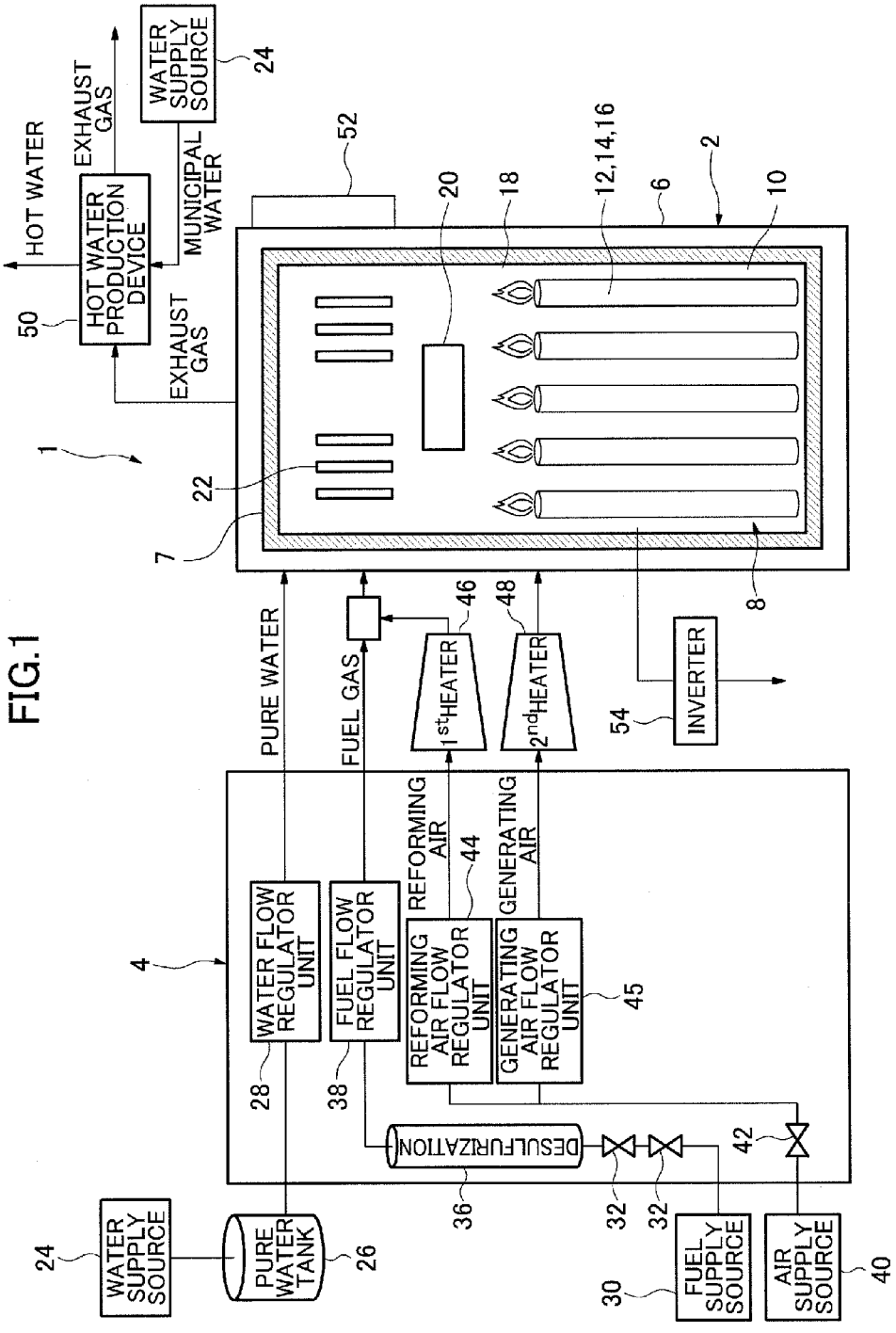


FIG.1


WATER SUPPLY SOURCE
24
EXHAUST GAS
HOT WATER
HOT WATER PRODUCTION DEVICE
50
MUNICIPAL WATER
EXHAUST GAS
1
52
20
18
12,14,16
6
2
10
22
7
8
PURE WATER
FUEL GAS
1st HEATER
46
2nd HEATER
48
INVERTER
54
4
WATER FLOW REGULATOR UNIT
FUEL FLOW REGULATOR UNIT
REFORMING AIR
GENERATING AIR
REFORMING AIR FLOW REGULATOR UNIT
GENERATING AIR FLOW REGULATOR UNIT
44
45
28
38
DESULFURIZATION
42
36
32
32
24
WATER SUPPLY SOURCE
PURE WATER TANK
26
30
FUEL SUPPLY SOURCE
AIR SUPPLY SOURCE
40

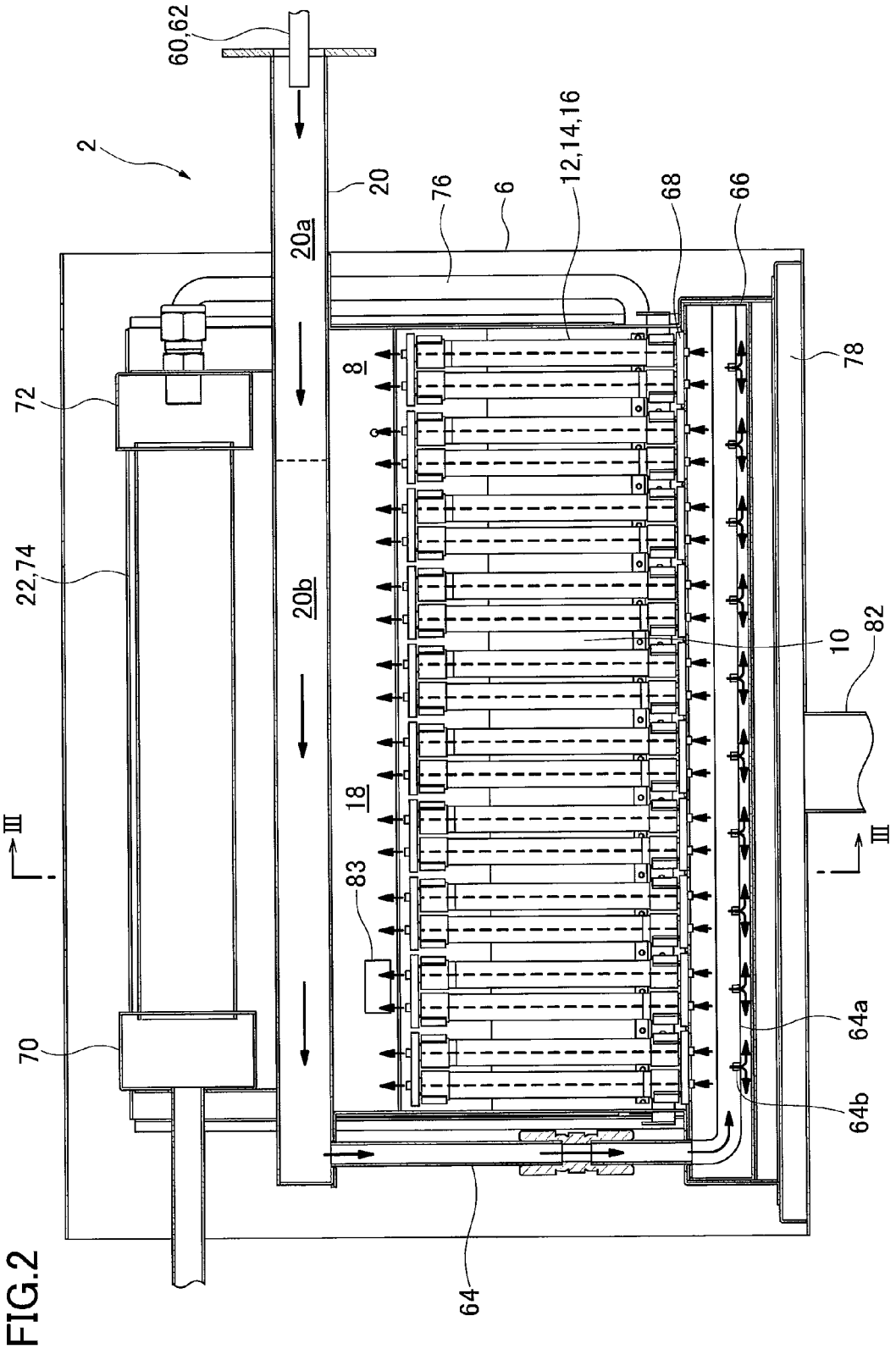

60,62
2
20
76
6
12,14,16
68
66
20a
78
72
8
22,74
20b
10
82
18
III
III
83
70
64a
64b
64

FIG.2

FIG.3

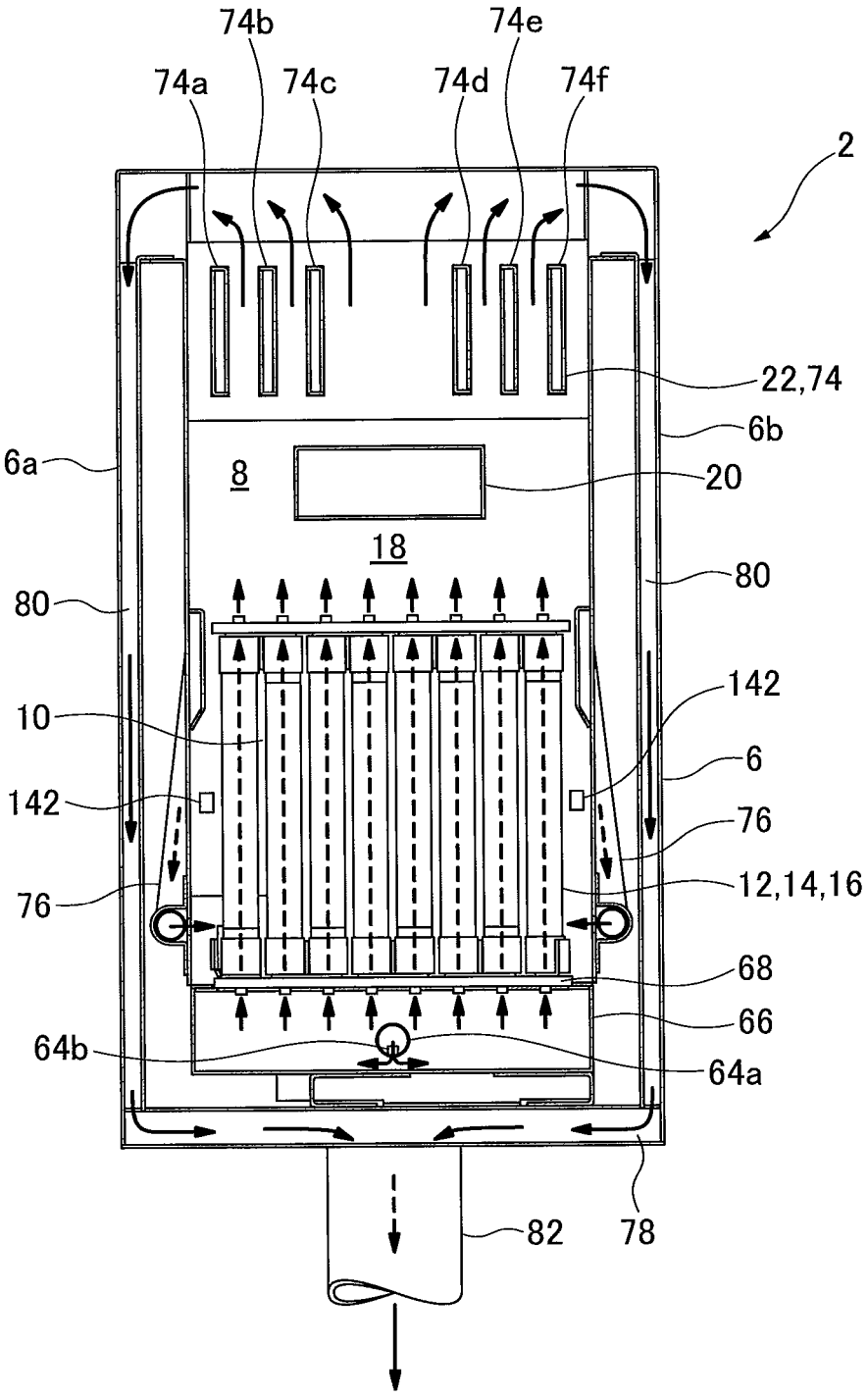

74b
74e
74a
74c
74d
74f
2
22,74
6b
6a
8
20
18
80
80
142
10
6
142
76
76
12,14,16
68
66
64b
64a
82
78

FIG.4

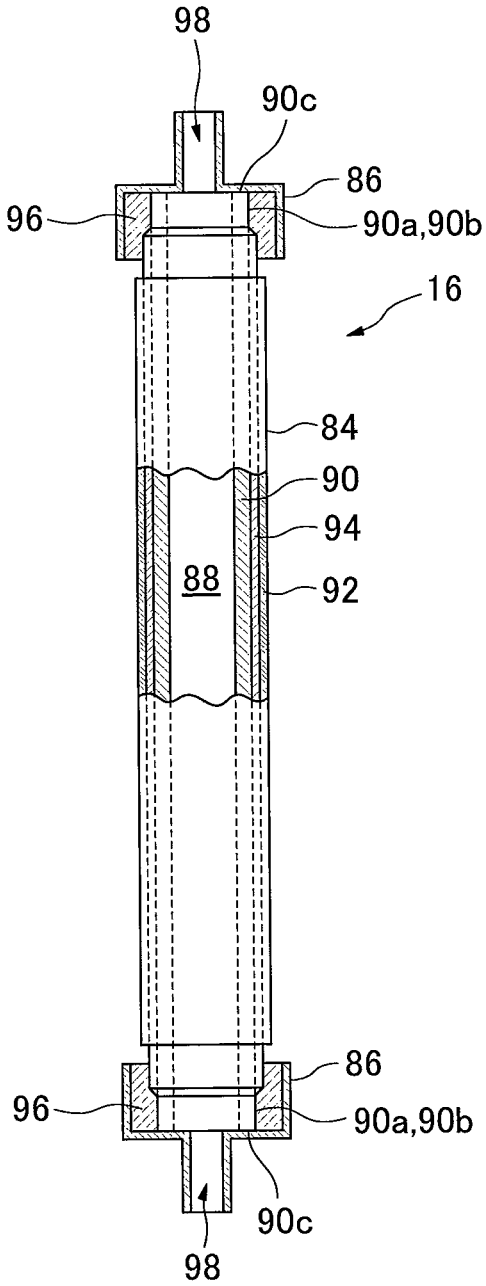


FIG.5

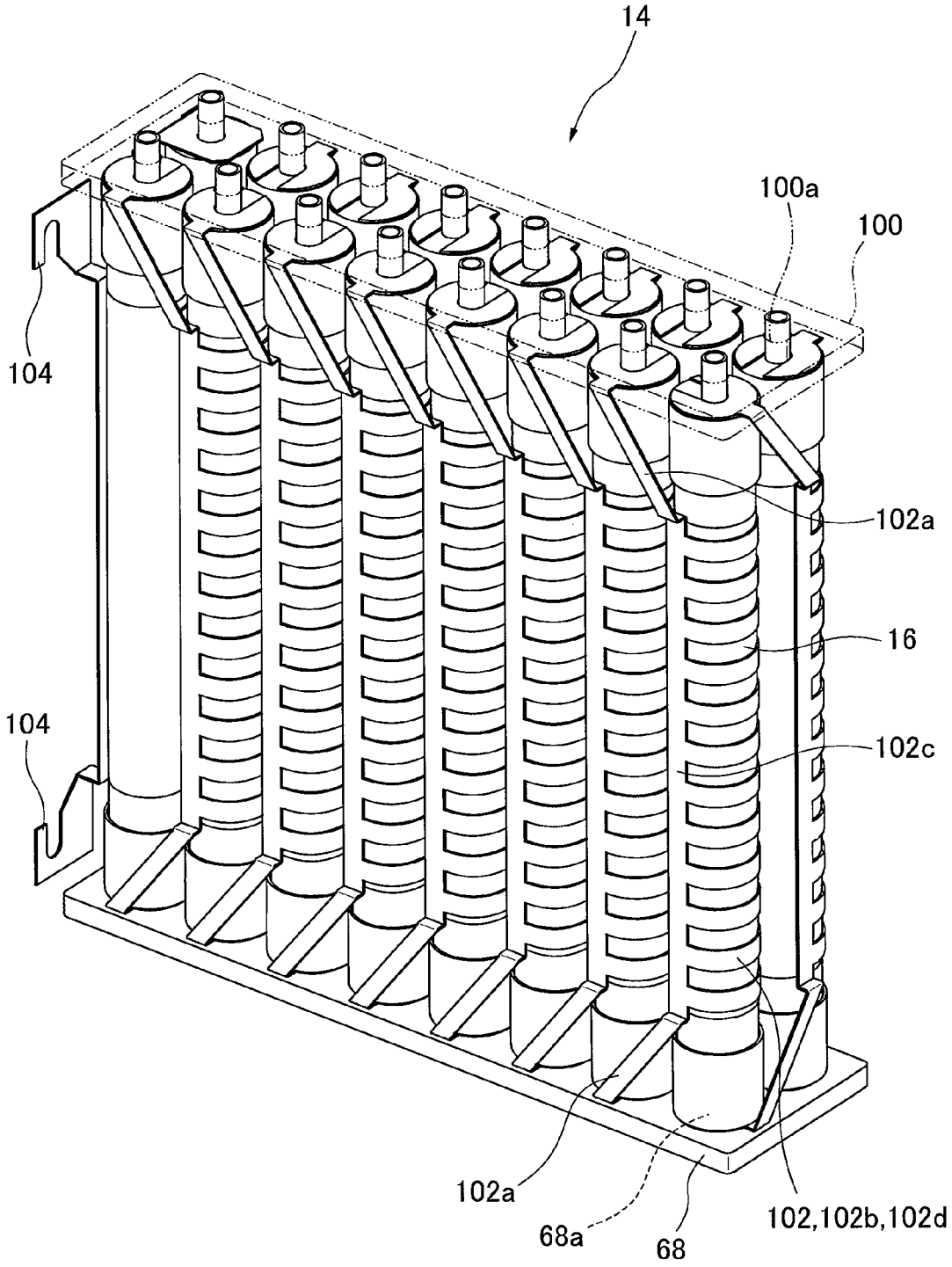


FIG.6

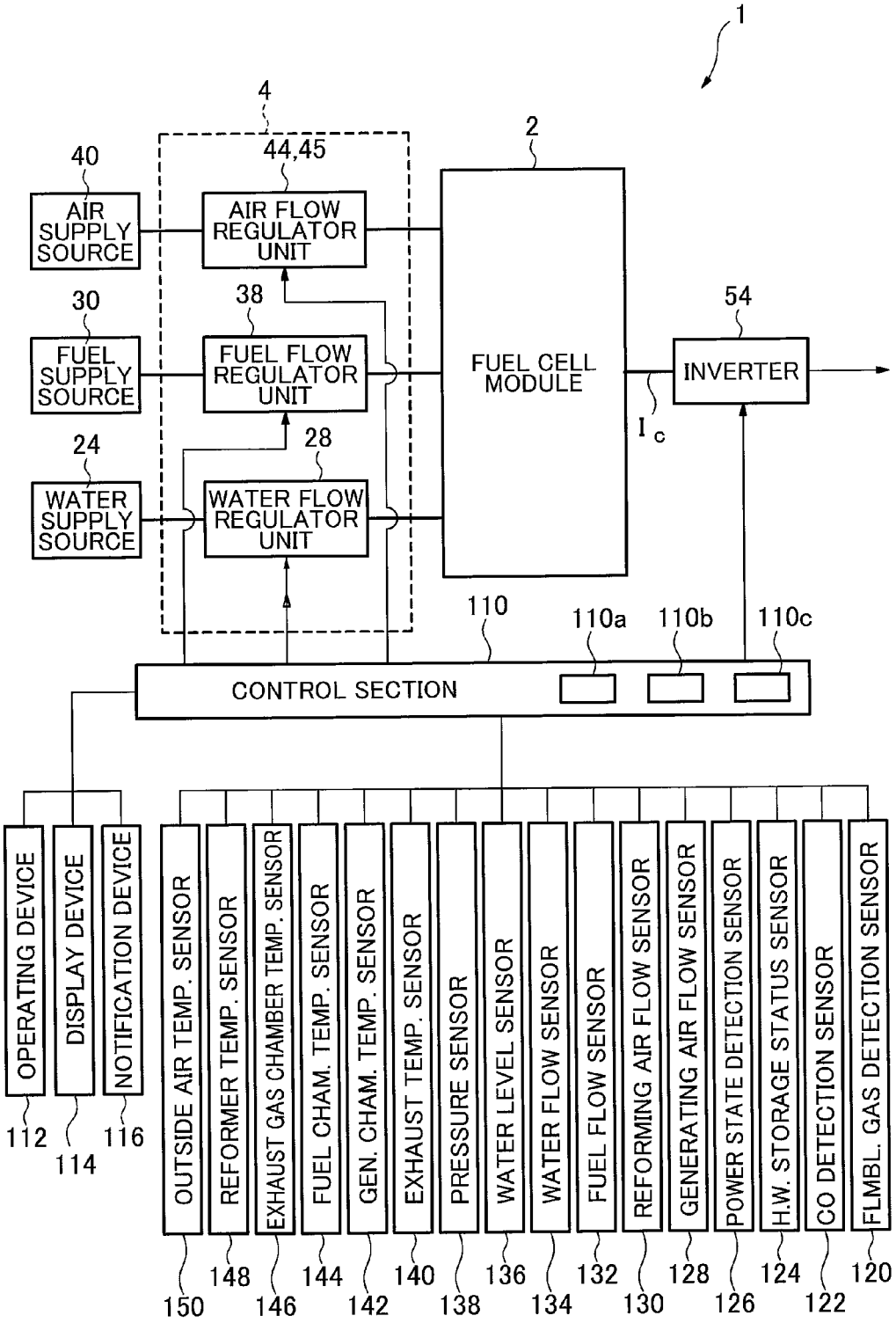

1
4
44,45
2
40
AIR SUPPLY SOURCE
AIR FLOW REGULATOR UNIT
30
38
FUEL SUPPLY SOURCE
FUEL FLOW REGULATOR UNIT
FUEL CELL MODULE
54
INVERTER
Ic
24
28
WATER SUPPLY SOURCE
WATER FLOW REGULATOR UNIT
110
110a
110b
110c
CONTROL SECTION
OPERATING DEVICE
DISPLAY DEVICE
NOTIFICATION DEVICE
OUTSIDE AIR TEMP. SENSOR
REFORMER TEMP. SENSOR
EXHAUST GAS CHAMBER TEMP. SENSOR
FUEL CHAM. TEMP. SENSOR
GEN. CHAM. TEMP. SENSOR
EXHAUST TEMP. SENSOR
PRESSURE SENSOR
WATER LEVEL SENSOR
WATER FLOW SENSOR
FUEL FLOW SENSOR
REFORMING AIR FLOW SENSOR
GENERATING AIR FLOW SENSOR
POWER STATE DETECTION SENSOR
H.W. STORAGE STATUS SENSOR
CO DETECTION SENSOR
FLMBL. GAS DETECTION SENSOR
112
114
116
150
148
146
144
142
140
138
136
134
132
130
128
126
124
122
120

FIG.7

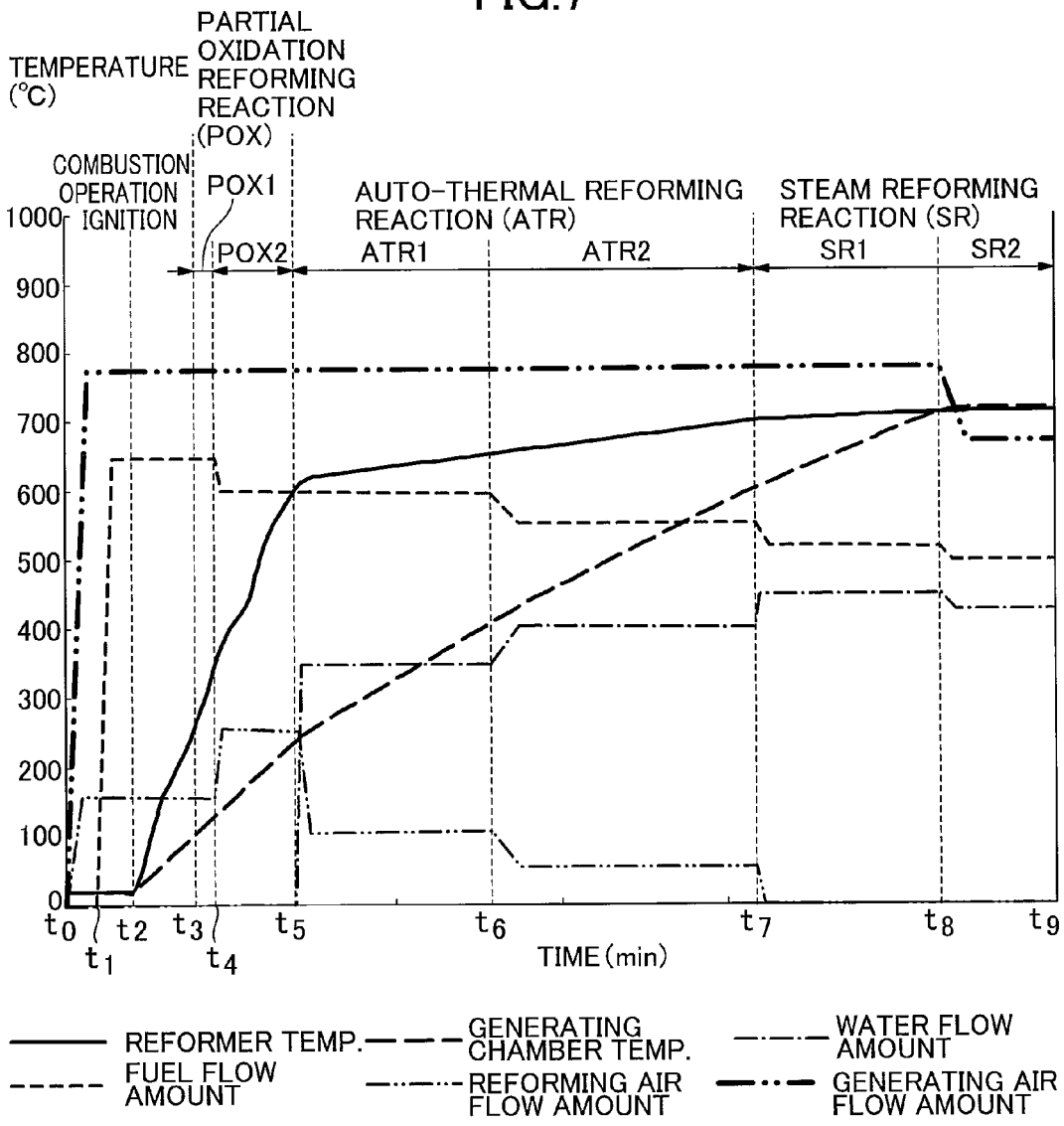

TEMPERATURE (°C)
PARTIAL OXIDATION REFORMING REACTION (POX)
COMBUSTION OPERATION IGNITION
POX1
POX2
AUTO-THERMAL REFORMING REACTION (ATR)
ATR1
ATR2
STEAM REFORMING REACTION (SR)
SR1
SR2
1000
900
800
700
600
500
400
300
200
100
0
t0
t1
t2
t3
t4
t5
t6
t7
t8
t9
TIME (min)
REFORMER TEMP.
GENERATING CHAMBER TEMP.
WATER FLOW AMOUNT
FUEL FLOW AMOUNT
REFORMING AIR FLOW AMOUNT
GENERATING AIR FLOW AMOUNT

FIG.8

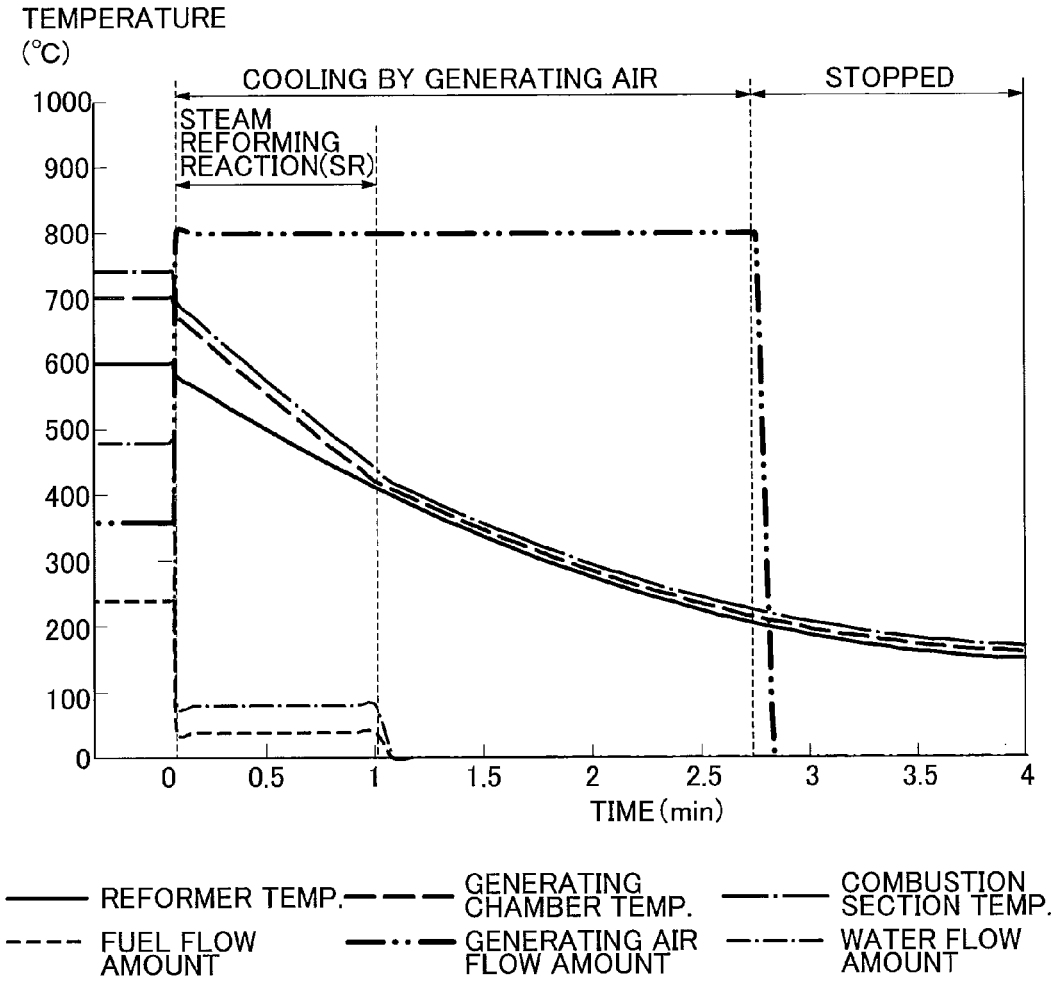

TEMPERATURE
(°C)
COOLING BY GENERATING AIR
STOPPED
STEAM
REFORMING
REACTION(SR)
1000
900
800
700
600
500
400
300
200
100
0
0
0.5
1
1.5
2
2.5
3
3.5
4
TIME (min)
REFORMER TEMP.
GENERATING CHAMBER TEMP.
COMBUSTION SECTION TEMP.
FUEL FLOW AMOUNT
GENERATING AIR FLOW AMOUNT
WATER FLOW AMOUNT

FIG.9

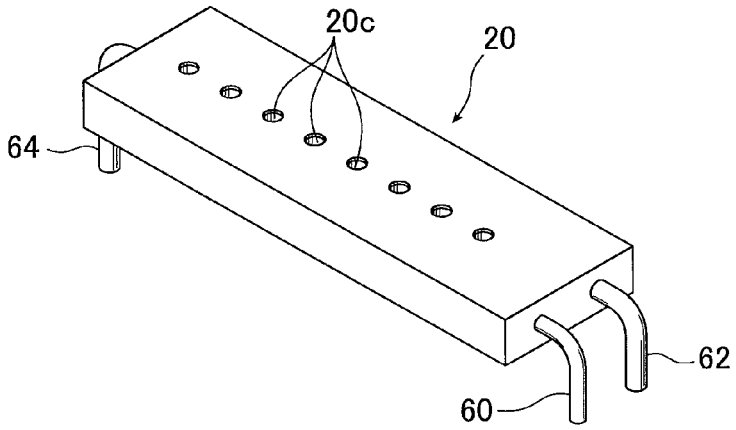


FIG.10

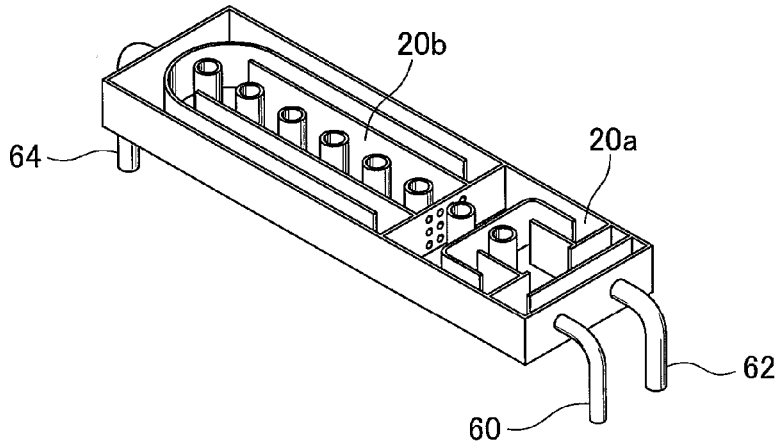


FIG.11

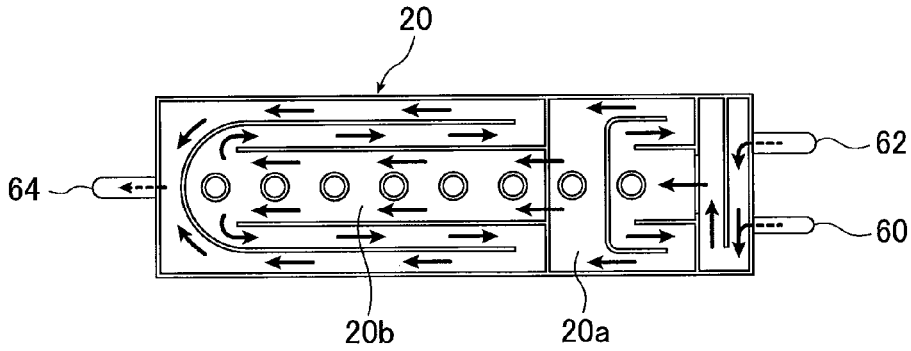


FIG.12

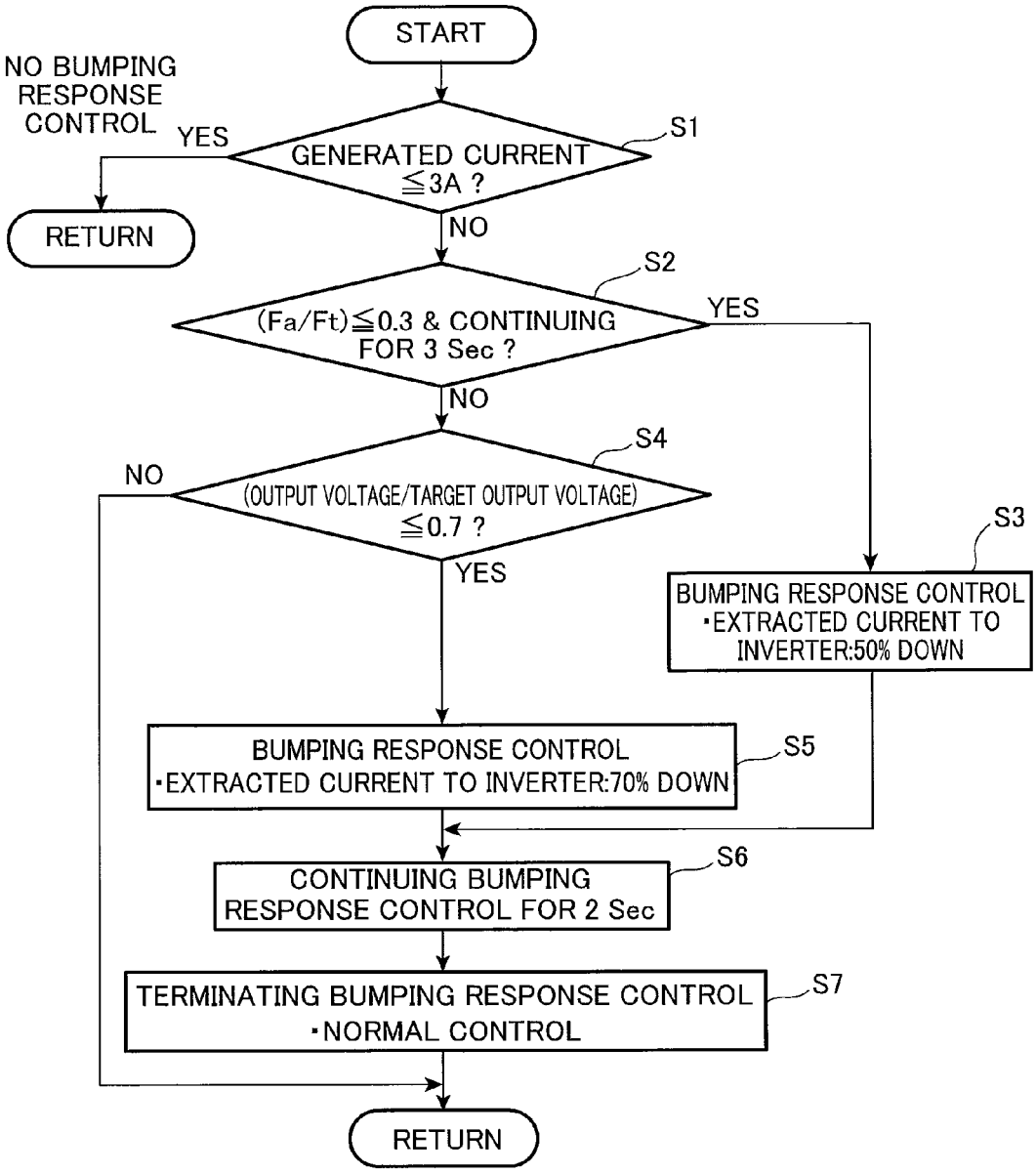

START
NO BUMPING RESPONSE CONTROL
YES
GENERATED CURRENT ≦3A ?
S1
RETURN
NO
S2
(Fa/Ft)≦0.3 & CONTINUING FOR 3 Sec ?
YES
NO
S4
NO
(OUTPUT VOLTAGE/TARGET OUTPUT VOLTAGE) ≦0.7 ?
YES
S3
BUMPING RESPONSE CONTROL
・EXTRACTED CURRENT TO INVERTER:50% DOWN
BUMPING RESPONSE CONTROL
・EXTRACTED CURRENT TO INVERTER:70% DOWN
S5
CONTINUING BUMPING RESPONSE CONTROL FOR 2 Sec
S6
TERMINATING BUMPING RESPONSE CONTROL
・NORMAL CONTROL
S7
RETURN

FIG.13

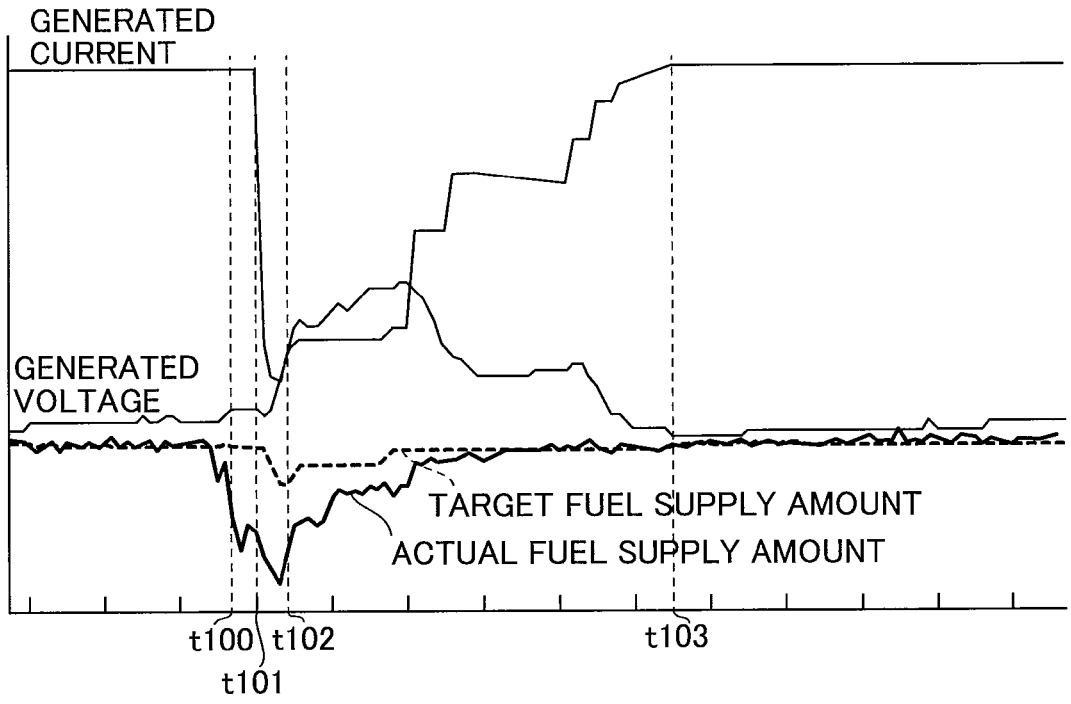

GENERATED CURRENT
GENERATED VOLTAGE
TARGET FUEL SUPPLY AMOUNT
ACTUAL FUEL SUPPLY AMOUNT
t100
t101
t102
t103

FIG.14

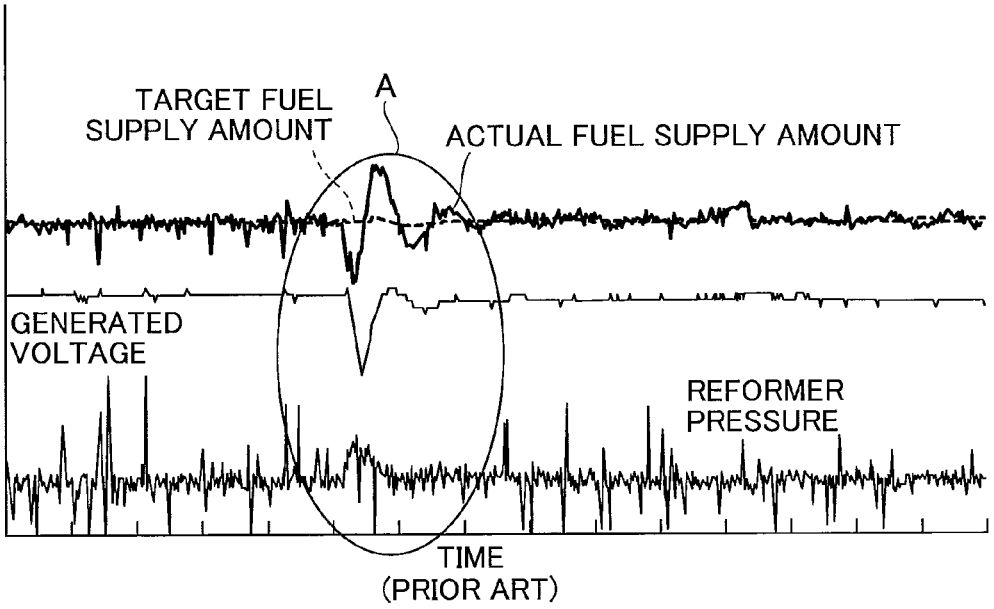
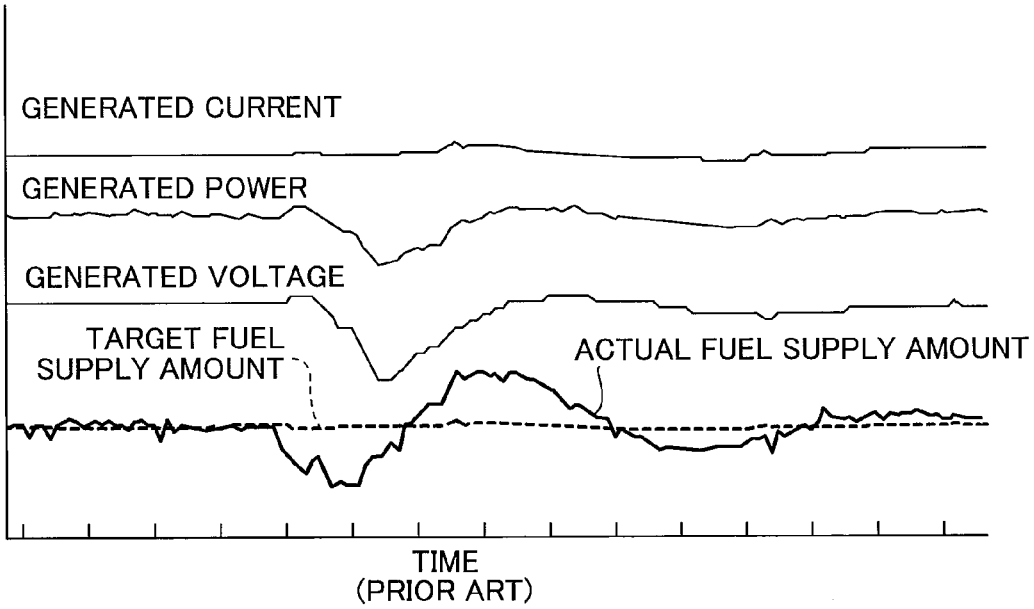

TARGET FUEL
SUPPLY AMOUNT
A
ACTUAL FUEL SUPPLY AMOUNT
GENERATED
VOLTAGE
REFORMER
PRESSURE
TIME
(PRIOR ART)

FIG.15


GENERATED CURRENT
GENERATED POWER
GENERATED VOLTAGE
TARGET FUEL
SUPPLY AMOUNT
ACTUAL FUEL SUPPLY AMOUNT
TIME
(PRIOR ART)

SOLID OXIDE FUEL CELL SYSTEM RESPONSIVE TO EXPLOSIVE VAPORIZATION OF WATER IN REFORMER TO CONTROL POWER

RELATED APPLICATIONS

This application claims priority under 35 U.S.C. §119 to Japanese Patent Application No. 2012-071364 filed on Mar. 27, 2012, the entire content of which is hereby incorporated by reference.

TECHNICAL FIELD

The present invention pertains to a solid oxide fuel cell, and more particularly to a solid oxide fuel cell in which supplied fuel is reformed by the addition of steam, and electrical power is produced using the reformed fuel.

BACKGROUND ART

Solid oxide fuel cells ("SOFC" below) use oxide ion conductive solid electrolytes; these are fuel cells which operate at comparatively high temperatures, to which electrodes are attached on both sides, and fuel gas is supplied to one side while oxidant (air, oxygen, etc.) is supplied to the other.

A fuel cell apparatus is described in Published Unexamined Patent Application 2010-277846 (Patent Document 1). In this solid oxide fuel cell apparatus, during the startup process a partial oxidation reforming reaction of the fuel, an autothermal reforming reaction in which the partial oxidation reforming reaction and steam reforming reaction are mixed, and a steam reforming reaction are successively caused to occur inside the reformer, and the temperatures of the reformer and the fuel cell stack are raised to the temperature at which the generating process is possible. Also, in this solid oxide fuel cell apparatus the fuel supply means, reforming air supply means, and water supply means are controlled so that a target fuel supply amount, target air supply amount, and target water supply amount are respectively supplied.

However in the fuel cell apparatus set forth in Published Unexamined Patent Application 2010-277846, water for steam reforming is intermittently supplied by a pulsed pump, so that after reforming water is supplied this water is vaporized in a short period, with the resulting problem that pressures inside the vaporization chamber and reformer temporarily rise. i.e., because it becomes difficult to supply fuel into the reformer when pressure inside the rated reference temperature is elevated, a fuel supply amount detection sensor detects the state whereby the fuel supply amount diminishes to less than the target amount under elevated pressure, judging immediately thereafter that fuel is insufficient, and performing an increase amount control to increase the supply of fuel. However, because in actuality the pressure drops in the next instant, it becomes easy to supply fuel, so that even though the above-described insufficient portion of fuel is not inherently required, it is still supplied, with the resulting problem that fuel is oversupplied.

This type of fuel oversupply problem occurs when there is an autothermal reforming reaction in the startup process, in which the amount of water supplied is particularly small. Therefore in the fuel cell apparatus set forth in Published Unexamined Patent Application 2010-277846, a stable autothermal reforming reaction can be implemented by suppressing changes in the amount of fuel supplied by the fuel supply means in the autothermal reforming reaction during the startup process.

PRIOR ART REFERENCES

Patent References

Patent Document 1
Published Unexamined Patent Application 2010-277846.

SUMMARY OF THE INVENTION

However, the present inventors discovered a new problem, which is that ill effects caused by instantaneous vaporization (bumping) of water of the type described in Published Unexamined Patent Application 2010-277846 occur not only when water is intermittently supplied, but also when it is continuously supplied. Additionally, they discovered the problem that ill effects caused by intermittent vaporization of water occur not only during the autothermal reforming reaction in the startup process, but also during generating operation, are associated with degradation of fuel cells. Moreover, during generating operation, per the invention set forth in Published Unexamined Patent Application 2010-277846, it is difficult to suppress changes in fuel supply amounts, and it has not been possible to sufficiently resolve the ill effects caused by instantaneous vaporization of water.

Therefore the present invention has the object of providing a solid oxide fuel cell with which the degradation of fuel cells can be suppressed by avoiding the ill effects caused by bumping of water used for steam reforming during electrical generating operation.

In order to resolve the above-described problems, the present invention is a solid oxide fuel cell system for generating electrical power using reformed fuel reformed by adding steam to supplied fuel, comprising: a fuel cell module including a fuel cell stack; a fuel supply device that supplies fuel; a reformer that reforms fuel supplied from the fuel supply device by adding steam to the supplied fuel and supplying same to the fuel cell stack; a vaporization chamber disposed on the upstream side of the reformer for supplying steam vaporized therein to the reformer; a water supply device that supplies water to the vaporization chamber; a controller programmed to control the fuel supply device and the water supply device, and to control the power extracted from the fuel cell module; wherein the controller includes a bumping determination circuit and an extracted power limiting circuit, wherein the bumping determination circuit determines the occurrence of excessive and sudden vaporization of water in the vaporization chamber, and wherein the extracted power limiting circuit limits power extracted from the fuel cell module when the bumping determination circuit determines that excess bumping of water is happen.

In the present invention thus constituted, the controller controls the fuel supply device and water supply device and also controls power extracted from the fuel cell module. Water supplied from the water supply device is vaporized in the vaporization chamber erected on the upstream side of the reformer; the reformer steam reforms fuel supplied from the fuel supply device using steam vaporized in the vaporization chamber, supplying it to the fuel cell stack built into the fuel cell module. A bumping determination device determines excessive bumping of water in the vaporization chamber,

and the extracted power limiting device limits power extracted from the fuel cell module if excessive bumping of water is determined.

Bumping, which is the rapid vaporization of water occurring in the vaporization chamber, is a phenomenon caused by temperature unevenness in the vaporization chamber, and is difficult to fully suppress even when water is continuously supplied. The present inventors discovered the new technical problem that this type of bumping also occurs frequently during fuel cell module generating operation, and also has a negative effect on the fuel cell stack when major bumping occurs inside the vaporization chamber. This is because when major bumping occurs within the vaporization chamber, pressure inside the reformer rises for a certain period, during which it is difficult to introduce fuel into the reformer, causing the fuel cell stack to temporarily go into a "fuel depletion" state or "fuel shortage" state. Occurrences of the "fuel depletion" state or "fuel shortage" state cause degradation of the fuel cell stack and shorten the usable life years of the fuel cell stack.

The present invention was undertaken to resolve such newly discovered technical problems; when there is a determination of excessive bumping of water in a vaporization chamber by a bumping determination circuit, power extracted from a fuel cell module is limited by an extracted power limiting circuit. Thus extraction of power exceeding electrical generation capacity from a fuel cell stack in which generating capacity has been lowered by the effects of bumping in the vaporization chamber is suppressed, therefore degradation of the fuel cell stack is suppressed, and usable life years can be dramatically increased.

Preferably, the present invention further comprises a dispersion chamber and a fuel supply amount detection circuit that detects the fuel supply amount fed into the reformer; wherein the dispersion chamber accumulates fuel reformed in the reformer and disperses and supplies the fuel to each of individual fuel cell units of the fuel cell stack, and wherein the bumping determination circuit determines that excessive bumping of water has occurred when the fuel supply amount detection circuit continuously detects a decrease of supplied fuel more than predetermined amount relative to a target fuel supply amount for a predetermined time duration or more.

In the present invention thus constituted, the dispersion chamber accumulates fuel reformed in the reformer and disperses and supplies reformed fuel to each of the individual fuel cell units. Therefore a time lag is produced after fuel introduced into the reformer diminishes until the effects thereof reach each of the individual fuel cell units. If the state of reduced fuel supply amount continues for a predetermined period or greater, the bumping determination circuit determines that excessive bumping of water has occurred.

In the present invention thus constituted, there is a time lag until the effects of fuel diminishment reach each of the individual fuel cell units, therefore the bumping determination circuit determines excessive bumping after confirming whether the drop in fuel supply amount has continued for a predetermined time period or not, and negative effects on each of the individual fuel cell units can be sufficiently suppressed even if power limiting is implemented. Thus the occurrence of excessive bumping can be accurately determined, and operation of the fuel cell module can be prevented from becoming unstable as the result of repeated unnecessary limitations of power caused by false determinations.

Preferably, the present invention further comprises an output voltage detection circuit for detecting the output voltage of the fuel cell module; wherein the bumping determination circuit determines that excessive bumping of water has occurred when the output voltage detection circuit detects a decrease of the output voltage more than predetermined amount relative to a target output voltage.

The present invention discovered a new technical problem, which is that reliably determining excessive bumping of an extent that will affect the generating capacity of a fuel cell stack is difficult. In the present invention thus constituted, excessive bumping of water is determined by a drop in output voltage, therefore reliable control of bumping can be executed even when excessive bumping of water can not be detected by a determination based on fuel supply amount. Also, because "fuel depletion" or "fuel shortages" based on excessive bumping of water continue for a certain period, ill effects on the fuel cell stack are sufficiently ameliorated even when responding to bumping after the occurrence of a drop in output voltage.

In the present invention the extracted power limiting circuit maintains power extraction from the fuel cell module at least a predetermined amount even when power extracted from the fuel cell module is being limited.

In general, even if excessive bumping occurs in the vaporization chamber, the amount of fuel supplied does not go to zero. In this type of state, completely stopping the extraction of power from the fuel cell module results in all of the supplied fuel being utilized to heat the inside of the fuel cell module, such that the temperature inside the fuel cell module rises excessively. In the present invention thus constituted, the extraction of power at or above a predetermined amount is maintained even when power is being limited, therefore excessive temperature rises in the fuel cell module can be prevented while avoiding "fuel depletion" or "fuel shortages" in the fuel cell stack.

In the present invention when the power generated by the fuel cell module is large, the extracted power limiting circuit limits the power extracted from the fuel cell module much more than when generated power is small.

In general, the solid oxide fuel cell is controlled so that the fuel utilization rate is high when generated power is large, and the fuel utilization rate is low when generated power is small. In the present invention thus constituted, power is more greatly limited when generated power is large than when it is small, therefore "fuel depletion" and "fuel shortage" can be reliably avoided when power is large, which is when the fuel utilization rate is high, while at the same time unnecessary limiting of power can be prevented when power is small.

In the present invention when electrical generation by the fuel cell module is below a predetermined amount, the extracted power limiting circuit does not limit power extracted from the fuel cell module.

In the present invention thus constituted, in the region in which generated power (current) is at or below a predetermined amount, where it is clear that "fuel depletions" or "fuel shortages" caused by excessive bumping do not occur, power limiting is not performed, therefore unnecessary power limiting can be avoided by a simple control. Also, in the small generated power state, frequent limiting of power reduces the occurrence of electrical generation heat, so that while there is a risk that the interior of the fuel cell module will be excessively cooled, this can be avoided using the present invention constituted as described above.

Using the present invention, degradation of fuel cells can be suppressed by avoiding the ill effects caused by bumping of water used for steam reforming during electrical generating operation.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is an overview diagram showing a solid oxide fuel cell according to an embodiment of the present invention.

FIG. **2** is a front elevation cross section showing the fuel cell module of a fuel cell apparatus according to an embodiment of the present invention.

FIG. **3** is a sectional diagram along line III-III in FIG. **2**.

FIG. **4** is a partial cross section showing an individual fuel cell unit in a fuel cell apparatus according to an embodiment of the present invention.

FIG. **5** is a perspective view showing a fuel cell stack in a fuel cell apparatus according to an embodiment of the present invention.

FIG. **6** is a block diagram showing a fuel cell assembly according to an embodiment of the present invention.

FIG. **7** is a timing chart showing the operation at startup of a fuel cell assembly according to an embodiment of the present invention.

FIG. **8** is a timing chart showing what occurs upon stopping the operation of a fuel cell according to an embodiment of the present invention.

FIG. **9** is a front elevation cross section showing the fuel cell module of a fuel cell apparatus according to an embodiment of the present invention.

FIG. **10** is a perspective view showing the interior of a reformer with the top plate removed with a reformer built into a fuel cell apparatus according to an embodiment of the present invention.

FIG. **11** is a plan view showing the flow of fuel inside a reformer built into a fuel cell apparatus according to an embodiment of the present invention.

FIG. **12** is a control flowchart for a solid oxide fuel cell apparatus according to an embodiment of the present invention.

FIG. **13** is a timing chart showing an example of the control results from the FIG. **12** flow chart.

FIG. **14** is a graph showing a time line example of the operational states of a conventional solid oxide fuel cell during electrical generating operation.

FIG. **15** is a diagram showing an expanded view of the part in which excessive bumping is occurring within the FIG. **14** graph.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Next, referring to the attached drawings, we discuss a solid oxide fuel cell (SOFC) according to an embodiment of the present invention.

FIG. **1** is an overview diagram showing a solid oxide fuel cell (SOFC) according to an embodiment of the present invention. As shown in FIG. **1**, the solid oxide fuel cell (SOFC) of this embodiment of the present invention is furnished with a fuel cell module **2** and an auxiliary unit **4**.

Fuel cell module **2** is furnished with a housing **6**, and a sealed space **8** is formed within this housing **6**, mediated by heat insulation **7**. Disposed on generating chamber **10**, which is the lower part of this sealed space **8**, is a fuel cell assembly **12** for carrying out a generating reaction using fuel and oxidant (air). This fuel cell assembly **12** is furnished with ten fuel cell stacks **14** (see FIG. **5**), and fuel cell stacks **14** comprise 16 fuel cell units **16** (see FIG. **4**). Thus, fuel cell assembly **12** has 160 fuel cell units **16**, all of which are serially connected.

A combustion chamber **18** is formed above the aforementioned generating chamber **10** in fuel cell module **2** sealed space **8**; residual fuel gas and residual oxidizer (air) not used in the electrical generation reaction are burned in this combustion chamber **18**, producing exhaust gas.

Disposed at the top of combustion chamber **18** is a reformer **20** for reforming fuel; this heats reformer **20** to a temperature at which the reforming reaction is possible using combustion heat from the residual gas. Furthermore, an air heat exchanger **22** is disposed on the top of this reformer **20** for receiving heat from the reformer **20** and heating air so as to restrain temperature drops in the reformer **20**.

Next, auxiliary unit **4** is furnished with a pure water tank **26** for holding water from a municipal or other water supply source **24** and filtering it into pure water, and a water flow regulator unit **28** (a "water pump" or the like driven by a motor) for regulating the flow volume of water supplied from the reservoir tank. Auxiliary unit **4** is furnished with a gas shutoff valve **32** for shutting off gas supplied from municipal gas or other fuel supply source **30**, a desulfurizer **36** for removing sulfur from fuel gas, and a fuel flow regulator unit **38** (a motor-driven "fuel pump" or the like) for regulating the flow volume of fuel gas. Furthermore, an auxiliary unit **4** is furnished with an electromagnetic valve **42** for shutting off air serving as an oxidizer and supplied from an air supply source **40**, a reforming airflow regulator unit **44** and generating airflow regulator unit **45** ("air blower" or the like driven by a motor) for regulating airflow volume, a first heater **46** for heating reforming air supplied to the reformer **20**, and a second heater **48** for heating generating air supplied to the generating chamber. This first heater **46** and second heater **48** are provided in order to efficiently raise the temperature at startup, but may be omitted.

Next, a hot-water producing device **50** supplied with exhaust gas is connected to the fuel cell module **2**. Municipal water from a water supply source **24** is supplied to this hot-water producing device **50**; this water is turned into hot water by the heat of the exhaust gas, and is supplied to a hot water reservoir tank in an external water heater, not shown.

A control box **52** for controlling the amount of fuel gas supplied, etc. is connected to the fuel cell module **2**.

Furthermore, an inverter **54** serving as an electrical power extraction unit (electrical power conversion unit) for supplying electrical power generated by the fuel cell module to the outside is connected to fuel cell module **2**.

The internal structure of the solid oxide fuel cell (SOFC) fuel cell module of this embodiment of the present invention is explained using FIGS. **2** and **3**. FIG. **2** is a side elevation sectional diagram showing a fuel cell module in a solid oxide fuel cell (SOFC) according to an embodiment of the present invention; FIG. **3** is a sectional diagram along line of FIG. **2**.

As shown in FIGS. **2** and **3**, starting from the bottom in the sealed space **8** within the fuel cell module **2** housing **6**, a fuel cell assembly **12**, a reformer **20**, and an air heat exchanger **22** are arranged in sequence, as described above.

A pure water guide pipe **60** for introducing pure water on the upstream end of reformer **20**, and a reform gas guide pipe **62** for introducing the fuel gas and reforming air to be reformed, are attached to reformer **20**; a vaporizing section **20***a* and a reforming section **20***b* are formed in sequence starting from the upstream side within reformer **20**, and

these reforming sections **20** *a* and **20***b* are filled with a reforming catalyst. Fuel gas and air blended with the steam (pure water) introduced into reformer **20** are reformed by the reforming catalyst used to fill in reformer **20**. Appropriate reforming catalysts are used, such as those in which nickel is imparted to the surface of aluminum spheres, or ruthenium is imparted to the surface of aluminum spheres.

A fuel gas supply line **64** is connected to the downstream end of reformer **20**; this fuel gas supply line **64** extends downward, then further extends horizontally within a manifold formed under fuel cell assembly **12**. Multiple fuel supply holes **64***b* are formed on the bottom surface of a horizontal portion **64***a* of fuel gas supply line **64**; reformed fuel gas is supplied into manifold **66** from these fuel supply holes **64***b*.

A lower support plate **68** provided with through holes for supporting the above-described fuel cell stack **14** is attached at the top of manifold **66**, and fuel gas in manifold **66** is supplied into fuel cell units **16**.

Next, an air heat exchanger **22** is provided over reformer **20**. This air heat exchanger **22** is furnished with an air concentration chamber **70** on the upstream side and two air distribution chambers **72** on the downstream side; this air concentration chamber **70** and the distribution chambers **72** are connected using six airflow conduits **74**. Here, as shown in FIG. **3**, three airflow conduits **74** form a set (**74***a*, **74***b*, **74***c*, **74***d*, **74***e*, **74***f*); air in the air concentration chamber **70** flows from each set of the airflow conduits **74** to the respective air distribution chambers **72**.

Air flowing in the six airflow conduits airflow conduits **74** of the air heat exchanger **22** is pre-heated by rising combustion exhaust gas from combustion chamber **18**.

Air guide pipes **76** are connected to each of the respective air distribution chambers **72**; these air guide pipes **76** extend downward, communicating at the bottom end side with the lower space in generating chamber **10**, and introducing preheated air into generating chamber **10**.

Next, an exhaust gas chamber **78** is formed below manifold **66**. As shown in FIG. **3**, an exhaust gas conduit **80** extending in the vertical direction is formed on the insides of front surface **6***a* and rear surface **6***b* which form the faces in the longitudinal direction of housing **6**; the top inside of exhaust gas chamber conduit **80** communicates with the space in which air heat exchanger **22** is disposed, and the bottom end side communicates with exhaust gas chamber **78**. An exhaust gas discharge pipe **82** is connected at approximately the center of the bottom surface of the exhaust gas chamber **78**; the downstream end of this exhaust gas discharge pipe **82** is connected to the above-described hot water producing device **50** shown in FIG. **1**.

As shown in FIG. **2**, an ignition device **83** for starting the combustion of fuel gas and air is disposed on combustion chamber **18**.

Next, referring to FIG. **4**, we discuss fuel cell units **16**. FIG. **4** is a partial section showing a solid oxide fuel cell (SOFC) fuel cell unit according to an embodiment of the present invention.

As shown in FIG. **4**, fuel cell units **16** are furnished with a fuel cell **84** and internal electrode terminals **86**, respectively connected to the respective terminals at the top and bottom of fuel cell **84**.

Fuel cell **84** is a tubular structure extending in the vertical direction, furnished with a cylindrical internal electrode layer **90**, on the inside of which is formed a fuel gas flow path **88**, a cylindrical external electrode layer **92**, and an electrolyte layer **94** between internal electrode layer **90** and external electrode layer **92**. This internal electrode layer **90** is a fuel electrode through which fuel gas passes, and is a (−) pole, while the external electrode layer **92** is an air electrode which contacts the air, and is a (+) pole.

The internal electrode terminals **86** attached at the top end and bottom end of fuel cell units **16** have the same structure, therefore we will here discuss specifically the internal electrode terminal **86** attached at the top and side. The top portion **90***a* of inside electrode layer **90** is furnished with an outside perimeter surface **90***b* and top end surface **90***c*, exposed to electrolyte layer **94** and outside electrode layer **92**. Inside electrode terminal **86** is connected to the outer perimeter surface of inside electrode layer **90** through a conductive seal material **96**, and is electrically connected to inside electrode layer **19** by making direct contact with the top end surface **90***c* of inside electrode layer **90**. A fuel gas flow path **98** communicating with the inside electrode layer **90** fuel gas flow path **88** is formed at the center portion of inside electrode terminal **86**.

Inside electrode layer **90** is formed, for example, from at least one of a mixture of Ni and zirconia doped with at least one type of rare earth element selected from among Ni, Ca, Y, Sc, or the like; or a mixture of Ni and ceria doped with at least one type of rare earth element; or any mixture of Ni with lanthanum gallate doped with at least one element selected from among Sr, Mg, Co, Fe, or Cu.

The electrolyte layer **94** is formed, for example, from at least one of the following: zirconia doped with at least one type of rare earth element selected from among Y, Sc, or the like; ceria doped with at least one type of selected rare earth element; or lanthanum gallate doped with at least one element selected from among Sr or Mg.

The outside electrode layer **92** is formed, for example, from at least one of the following: lanthanum manganite doped with at least one element selected from among Sr or Ca; lanthanum ferrite doped with at least one element selected from among Sr, Co, Ni, or Cu; lanthanum cobaltite doped with at least one element selected from among Sr, Fe, Ni, or Cu; silver, or the like.

Next, referring to FIG. **5**, we discuss fuel cell stack **14**. FIG. **5** is a perspective view showing the fuel cell stack in a solid oxide fuel cell (SOFC) according to an embodiment of the present invention.

As shown in FIG. **5**, fuel cell stack **14** is furnished with sixteen fuel cell units **16**; the top inside and bottom inside of these fuel cell units **16** are respectively supported by a lower support plate **68** and upper support plate **100**. Through holes **68***a* and **100***a*, through which the inside electrode terminal **86** can penetrate, are provided on this lower support plate **68** and outer support plate **100**.

In addition, a collector **102** and an external terminal **104** are attached to fuel cell units **16**. This collector **102** is integrally formed by a fuel electrode connecting portion **102***a*, which is electrically connected to inside electrode terminal **86** attached to inside electrode layer **90** serving as the fuel electrode, and by an air electrode connecting portion **102***b*, which is electrically connected to the entire external perimeter of outside electrode layer **92** serving as the air electrode. The air electrode connecting portion **102***b* is formed of a vertical portion **102***c* extending vertically along the surface of outside electrode layer **92**, and multiple horizontal portions **102***d* extending in the horizontal direction from this vertical portion **102***c* along the surface of outside electrode layer **92**. Fuel electrode connecting portion **102***a* extends linearly in an upward or downward diagonal direction from the vertical portion **102***c* of air electrode

connecting portion **102***b* toward inside electrode terminals **86** positioned in the upper and lower directions on fuel cell units **16**.

Furthermore, electrode terminals **86** at the top and bottom ends of the two fuel cell units **16** positioned at the end of fuel cell stack **14** (at the front and back sides on the left edge in FIG. **5**) are respectively connected to outside terminals **104**. These external terminals **104** are connected to external terminals **104** (not shown) at the ends of adjacent fuel cell stack **14**, and as described above, all of the 160 fuel cell units **16** are connected in series.

Next, referring to FIG. **6**, we discuss the sensors attached to the solid oxide fuel cell (SOFC) according to the present embodiment. FIG. **6** is a block diagram showing a solid oxide fuel cell (SOFC) according to an embodiment of the present invention.

As shown in FIG. **6**, a solid oxide fuel cell device **1** is furnished with a control unit **110**; connected to this control section **110** are: an operating device **112** provided with operating buttons such as "ON" or "OFF" for user operation, a display device **114** for displaying various data such as a generator output value (Watts), and a notification device **116** for issuing warnings during abnormal states and the like. This notification device **116** may also be one which is be connected to a remote control center to inform this control center of abnormal states.

Next, signals from the various sensors described below are input to control unit **110**.

First, flammable gas detection sensor **120** is for detecting gas leaks; it is attached to fuel cell module **2** and auxiliary unit **4**.

The purpose of flammable gas detection sensor **120** is to detect whether CO in the exhaust gas, which is supposed to be exhausted to the outside via exhaust gas conduit **80**, has leaked into the external housing (not shown) which covers fuel cell module **2** and auxiliary unit **4**.

A water reservoir state detection sensor **124** detects the temperature and amount of hot water in a water heater (not shown).

An electrical power state detection sensor **126** detects current, voltage, and the like in inverter **54** and in a distribution panel (not shown).

A generator airflow detection sensor **128** detects the flow volume of generator air supplied to generating chamber **10**.

A reforming airflow volume sensor **130** detects the volume of reforming airflow supplied to reformer **20**.

A fuel flow volume sensor **132** detects the flow volume of fuel gas supplied to reformer **20**.

A water flow volume sensor **134** detects the flow volume of pure water supplied to reformer **20**.

A water level sensor **136** detects the water level in pure water tank **26**.

A pressure sensor **138** detects pressure on the upstream side outside reformer **20**.

An exhaust temperature sensor **140** detects the temperature of exhaust gas flowing into hot water producing device **50**.

As shown in FIG. **3**, a generating chamber temperature sensor **142** is disposed on the front surface side and rear surface side around fuel cell assembly **12**; its purpose is to detect the temperature near fuel cell stack **14** and estimate the temperature of fuel cell stack **14** (i.e., of the fuel cell **84** itself).

A combustion chamber temperature sensor **144** detects the temperature in combustion chamber **18**.

An exhaust gas chamber temperature sensor **146** detects the temperature of exhaust gases in exhaust gas chamber **78**.

A reformer temperature sensor **148** detects the temperature of reformer **20** and calculates the reformer **20** temperature from the intake and exit temperatures on reformer **20**.

If the solid oxide fuel cell (SOFC) is placed outdoors, outside temperature sensor **150** detects the temperature of the outside atmosphere. Sensors to detect outside atmospheric humidity and the like may also be provided.

Signals from these various sensor types are sent to control unit **110**; control unit **110** sends control signals to water flow regulator unit **28**, fuel flow regulator unit **38**, reforming airflow regulator unit **44**, and generating airflow regulator unit **45** based on data from the sensors, and controls the flow volumes in each of these units.

Next, referring to FIG. **7**, we discuss the operation of a solid oxide fuel cell (SOFC) according to the present embodiment at the time of start up. FIG. **7** is a timing chart showing the operations of a solid oxide fuel cell (SOFC) according to an embodiment of the present invention at the time of start up.

At the beginning, operation starts in a no-load state, i.e., with the circuit which includes fuel cell module **2** in an open state, in order to warm up fuel cell module **2**. At this point current does not flow in the circuit, therefore fuel cell module **2** does not generate electricity.

First, reforming air is supplied from reforming airflow regulator unit **44** to reformer **2** on fuel cell module **2**. At the same time, generating air is supplied from generating airflow regulator unit **45** to fuel cell module **2** air heat exchanger **22**, and this generating air reaches generating chamber **10** and combustion chamber **18**.

Immediately thereafter, fuel gas is also supplied from fuel flow regulator unit **38**, and fuel gas into which reforming air is blended passes through reformer **20**, fuel cell stack **14**, and fuel cell units **16** to reach combustion chamber **18**.

Next, ignition is brought about by the ignition device **83**, and fuel gas and air (reforming air and generating air) supplied to combustion chamber **18** is combusted. This combustion of fuel gas and air produces exhaust gas; generating chamber **10** is warmed by this exhaust gas, and when the exhaust gas rises into fuel cell module **2** sealed space **8**, the fuel gas, which includes reforming air in reformer **20**, is warm, as is the generating air inside air heat exchanger **22**.

At this point, fuel gas into which reforming air is blended is supplied to reformer **20** by fuel flow regulator unit **38** and reforming airflow regulator unit **44**, therefore the partial oxidation reforming reaction POX given by Expression (1) proceeds. This partial oxidation reforming reaction POX is an exothermic reaction, and therefore has favorable starting characteristics. This elevated-temperature fuel gas is supplied from fuel gas supply line **64** to the bottom of fuel cell stack **14**, and by this means fuel cell stack **14** is heated from the bottom; combustion chamber **18** is also heated by the combustion of the fuel gas and air, so that fuel stack **14** is also heated from above, thereby enabling an essentially uniform rise in temperature in the vertical direction of fuel cell stack **14**. Even though the partial oxidation reforming reaction POX is progressing, the ongoing combustion reaction between fuel gas and air is continued in combustion chamber **18**.

$$C_mH_n+xO_2\rightarrow aCO_2+bCO+cH_2 \quad (1)$$

After the partial oxidation reforming reaction starts, when fuel cell stack **14** senses that reformer **20** has reached a predetermined temperature (e.g., 600° C.), a premixed gas of fuel gas and reforming air is supplied to reformer **20** by water flow regulator unit **28**, fuel flow regulator unit **38**, and reforming airflow regulator unit **44**. At this point, an auto-

thermal reforming reaction ATR, which makes use of both the aforementioned partial oxidation reforming reaction POX and the steam reforming reaction SR described below, proceeds in reformer **20**. This auto-thermal reforming reaction ATR can be internally thermally balanced, therefore the reaction proceeds in a thermally independent fashion inside reformer **20**. In other words, if oxygen (air) is abundant, heat emission by the partial oxidation reforming reaction POX dominates, and if steam is abundant, the endothermic steam reforming reaction SR dominates. At this stage, the initial stage of startup has passed and some degree of elevated temperature has been achieved within generating chamber **10**, therefore even if the endothermic reaction is dominant, no major drop in temperature will be caused. Also, the combustion reaction continues within combustion chamber **18** even as the auto-thermal reforming reaction ATR proceeds.

When reformer temperature sensor **146** senses that reformer **20** has reached a predetermined temperature after starting autothermal reforming reaction ATR (e.g., 700° C.), the supply of reforming air by reforming airflow regulator unit **44** is stopped and the supply of steam by water flow regulator unit **28** is increased. A gas containing no air and only containing fuel gas and steam is thus supplied to the reformer **20**, where the steam reforming reaction SR of Expression (3) proceeds.

$$C_mH_n+XO_2+yH_2O\rightarrow aCO_2+bCO+cH_2 \quad (2)$$

$$C_mH_n+xH_2O\rightarrow aCO_2+bCO+cH_2 \quad (3)$$

This steam reforming reaction SR is an endothermic reaction, therefore the reaction proceeds as thermal balance is maintained with the combustion heat from combustion chamber **18**. At this stage, the fuel cell module is in the final stages of startup, therefore the temperature has risen to a sufficiently high level within generating chamber **10** so that no major temperature dropped is induced in generating chamber **10** even though an endothermic reaction is proceeding. Also, the combustion reaction continues to proceed in combustion chamber **18** even as the steam reforming reaction SR is proceeding.

Thus, after fuel cell module **2** has been ignited by ignition device **83**, the temperature inside generating chamber **10** gradually rises as a result of the partial oxidation reforming reaction POX, the auto-thermal reforming reaction ATR, and the steam reforming reaction SR proceeding in sequence. Next, when the temperatures of interior of generating chamber **10** and individual fuel cells **84** reach a predetermined generating temperature below the rated temperature at which fuel cell module **2** can be stably operated, the circuit including fuel cell module **2** is closed and electrical generation by fuel cell module **2** begins, such that current flows in the circuit. Generation of electricity by fuel cell module **2** causes fuel cell **84** itself to emit heat, such that the temperature of fuel cell **84** rises. As a result, the rated temperature for operating fuel cell module **2**, for example 600° C. to 800° C., is reached.

Thereafter, in order to maintain the rated temperature, fuel gas and air are supplied in a quantity greater than the fuel gas and air consumed by individual fuel cells **84**. During electrical generation, generation of electricity by the high reforming efficiency steam reforming reaction SR proceeds.

Next, referring to FIG. **8**, we discuss the operation upon stopping the solid oxide fuel cell (SOFC) of the present embodiment. FIG. **8** is a timing chart showing what occurs upon stopping the operation of solid oxide fuel cell (SOFC) of the present embodiment.

As shown in FIG. **8**, when the operation of fuel cell module **2** is stopped, fuel flow regulator unit **38** and water flow regulator unit **28** are first controlled to reduce the quantity of fuel gas and steam being supplied to reformer **20**.

When stopping the operation of the fuel cell module **2**, the amount of generating air supplied by reforming airflow regulator unit **44** into fuel cell module **2** is being increased at the same time that the amount of fuel gas and steam being supplied to reformer **20** is being reduced; fuel cell assembly **12** and reformer **20** are air cooled to reduce their temperatures. Thereafter when the reformer **20** temperature has dropped to a predetermined temperature, for example to 400° C., supply of fuel gas and steam to the reformer **20** is stopped, and the reformer **20** steam reforming reaction SR ends. Supply of generating air continues until the temperature in reformer **20** reaches a predetermined temperature, e.g. 200° C.; when the predetermined temperature is reached, the supply of generating air from generating airflow regulator unit **45** is stopped.

Thus in the present embodiment the steam reforming reaction SR by reformer **20** and cooling by generating air are used in combination, therefore when operation of the fuel cell module **2** is stopped, that operation can be stopped relatively quickly.

Next, referring to FIGS. **9** through **11**, we discuss the detailed constitution of reformer **20**.

FIG. **9** is a perspective view of reformer **20**; FIG. **10** is a perspective view showing the interior of reformer **20** with the top plate removed. FIG. **11** is a plan view section showing the flow of fuel in reformer **20**.

As shown in FIG. **9**, reformer **20** is a parallepiped-shaped metal box disposed on top of fuel cell stack **14** inside fuel cell module **2**, the interior of which is filled with a reforming catalyst for reforming fuel. Connected on the upstream side of reformer **20** is a pure water infeed pipe **60** for introducing water and a reformed gas infeed pipe **62** for introducing fuel and reforming air. In addition, connected on the downstream side of reformer **20** is a fuel gas supply pipe **64** for discharging fuel reformed in the interior of reformer **20**. There are also eight air passage openings **20***c* placed in the longitudinal direction on reformer **20**. These reformers **20** are placed so as to penetrate from the bottom surface to the top surface of reformer **20** in such a way that combustion gas combusted in combustion chamber **18** (FIG. **2**) at the bottom of reformer **20** will be smoothly removed from the top of reformer **20**, and air passage openings **20***c* do not communicate with the interior of reformer **20**.

As shown in FIG. **10**, placed on the interior of reformer **20** on the upstream side is a steam generating section **20***a*, which is a steam generating chamber; placed adjacent to this steam generating section **20***a* on the downstream side is a reformer section **20***b*. A twisted passageway is formed within steam generating section **20***a* by the disposition of multiple partitioning plates. Water introduced from the water flow regulator unit **28**, being a water supply device, to reformer **20** is vaporized inside vaporizing section **20***a* in an elevated temperature state, and becomes steam. Fuel gas and reforming air introduced into reformer **20** are mixed with steam as they pass through a twisting and turning passageway in vaporizing section **20***a*. Note that in the present embodiment vaporizing section **20***a* and reformer section **20***b* are formed as an integral unit inside reformer **20**, but vaporizing section (steam producing chamber) **20***a* and reformer section **20***b* may also be separately constituted.

At the same time, a twisted passageway is formed inside reformer section **20***b*, as well, by the disposition of multiple partitioning plates, and is filled with catalyst. Fuel gas and

reforming air blended in vaporizing section **20***a* are subjected to the partial oxidation reforming reaction as they pass through the passageway in reformer section **20***b*. When a mixture of fuel gas, steam, and reforming air are introduced from vaporizing section **20***a*, a partial oxidation reforming reaction and a steam reforming reaction occur in reformer section **20***b*. Furthermore, when a mixture of fuel gas, steam, and reforming air are introduced from vaporizing section **20***a*, only the steam reforming reaction occurs in reformer section **20***b*.

As shown in FIG. **11**, fuel gas, water, and reforming air introduced into the reformer **20** steam generating section **20***a* first flows in a snaking manner in the lateral direction of reformer **20**, then is split into two passageways and snakes in the longitudinal direction of reformer **20**. Furthermore, the passageways then re-merge and are connected to reformer section **20***b* at the center part of reformer **20**. After flowing longitudinally at the center of reformer **20**, fuel and the like introduced into reformer section **20***b* are branched into two parts and doubled back; the two passageways again double back and move toward the downstream end of reformer section **20***b*; there they are merged, flowing into fuel gas supply pipe **64**. As it thus passes through the snaking passageway, fuel etc. is reformed by the catalyst with which the passageway is filled.

Next, referring to FIGS. **14** and **15**, we discuss the bumping phenomenon in the vaporizing section of a conventional solid oxide fuel cell. FIG. **14** is a graph showing a time line example of the operational states of a conventional solid oxide fuel cell during electrical generating operation. FIG. **15** shows an expanded view of the part in which excessive bumping is occurring within the FIG. **14** graph.

In the topmost graph in FIG. **14**, the dotted line shows target fuel supply values, and the solid line shows actual fuel supply amounts. The middle graph in FIG. **14** is the output voltage from the fuel cell module, and the bottom graph shows pressure inside the vaporizing section of the reformer. FIG. **15** shows an expanded view of the time axis in the part of FIG. **14** where excessive bumping is occurring; the top graph shows generated current, the second graph generated power, the third graph the output voltage of the fuel cell module; in the bottom graph the dotted line shows target fuel supply values, and the solid line shows actual fuel supply amounts.

As shown by the bottommost graph in FIG. **14**, pressure inside the reformer fluctuates dramatically over time. The primary reason for such pressure fluctuations is believed to be the bumping phenomenon, whereby tiny amounts of water droplets in the reformer boil instantaneously. I.e., because the volume of water expands by approximately 300 times when boiled, the pressure inside the reformer rises suddenly as water is boiled. Thus the bumping phenomenon occurs extremely frequently, and even if water is supplied continuously it is difficult to completely eliminate the occurrence of bumping. However, the majority of bumping-induced pressure fluctuations inside a reformer are concentrated in an extremely short time period, and do not greatly affect the flow volume of fuel gas introduced into the reformer. In addition, there is virtually no change in the fuel cell module output-voltage even if pressures inside the reformer fluctuate severely. This is thought to be because fuel flowing out of the reformer is generally first stored in the manifold, which is a dispersion chamber, then distributed from there to multiple fuel cell units. I.e., it is believed that fluctuations in fuel supply amount caused by short duration pressure fluctuations are made uniform inside the manifold, and have virtually no effect on the fuel actually distributed to each of the fuel cell units.

However, in the part shown as A in FIG. **14**, major bumping occurs, and pressures inside the reformer rise over a relatively long time period. In addition, as is clear from FIG. **15**, in which the time axis is expanded for the part in which transient bumping occurs, there are also large fluctuations in the flow volumes of fuel gas introduced into the reformer when excess bumping occurs in this manner. As shown in the bottom portion of FIG. **15**, when excessive bumping occurs, the fuel supply amounts introduced into the reformer are reduced over a comparatively long time. Feedback control acts on such reductions in fuel gas supply amounts, and fuel supply amounts are brought into convergence with fuel supply target values as overshooting is repeated. However, as shown in the third graph of in FIG. **15**, after approximately 5 seconds following the start of reduction in the fuel supply amount, the output voltage of the fuel cell module begins to drop. This drop in output voltage is caused by a drop in the concentration of fuel supplied to each of the fuel cell units due to the temporary drop in fuel supply amount, causing the generating capacity of each fuel cell unit to drops. I.e., it is believed that a voltage drop occurs because a fixed current is extracted from the fuel cell module, even though in this state the fuel supply amount and generating capacity have dropped.

Thus the present inventors have discovered a new technical problem in that when the generating capacity of each fuel cell unit has dropped, each of the fuel cell units temporarily goes into a state close to "fuel depletion" due to the extraction of current (power) higher than generating capacity, causing degradation in each of the fuel cell units to advance. As described above, bumping of steam reforming water occurs frequently in the reformer vaporizing section, and it has been difficult to avoid the occurrence of such bumping. In addition, because a large amount of such bumping is small in scale, effects are minor on actual fuel supply amounts, generating capacity of each fuel cell unit, and the like. However there is also large-scale bumping among the frequently occurring bumping, and when such excessive boiling of water occurs, the actual fuel supply amount drops for a certain time period and the associated "fuel depletion" or "fuel shortage" causes the advance of the degradation of each fuel cell units, reducing the number of usable years of the fuel cell units. The present invention was undertaken to resolve such technical problems.

Next, referring to the FIGS. **12** and **13**, we discuss control in a solid oxide fuel cell **1** according to an embodiment of the present invention.

FIG. **12** is a control flowchart for the solid oxide fuel cell **1** of the present embodiment. FIG. **13** is a timing chart showing an example of the control results in the FIG. **12** flow chart.

The flow chart shown in FIG. **12** is a control subroutine to respond to excessive bumping occurring in the vaporizing section **20***a* of reformer **20**, and is executed at a predetermined time cycle during the electrical generating operation of solid oxide fuel cell **1**.

First, at step **S1** in FIG. **12**, a judgment is made as to whether current generated by fuel cell module **2** is at or below a predetermined current. In the present embodiment, when generated current is greater than 3 A, the system advances to step **S2**; when less than or equal to 3 A, one iteration of the processing shown in the FIG. **12** flow chart is completed. I.e., control to counter bumping is not executed when generated current is 3 A or less; when greater

than 3 A, control to counter bumping is executed as needed. Note that in the present embodiment, a judgment of whether or not to perform control for bumping is made based on fuel cell module **2** generated current, but a determination can also be made based on generated power.

In the solid oxide fuel cell **1** of the present embodiment an oxide ion conductive solid electrolyte is used as the electrolyte, and electrical generation is carried out with the interior of fuel cell module **2** maintained at a relatively high generating temperature. Therefore a portion of supplied fuel does not contribute to electrical generation, but is instead used to maintain the generating temperature inside fuel cell module **2**. As described above, when residual fuel flowing through the inside of each individual fuel cell unit **16** remains without being used to generate electricity, it is combusted when it flows down from the top end of each of the individual fuel cell units **16**; this combustion heat is then used to maintain the temperature inside fuel cell module **2**. Thus since a predetermined amount of supplied fuel is used to maintain temperature inside fuel cell module **2**, the fuel utilization rate (the portion of supplied fuel utilized for electrical generation) is set to be high in the region where the generated current (generated power) at which an increase in the amount of fuel used for electrical generation occurs is set high, and is set low in the region where generating current (generating power) is small.

Therefore in the small generated current region in which generated current is 3 A or less, the fuel utilization rate is set low, so fuel approximately equal to what is used for electrical generation is supplied even when the fuel supply amount has temporarily dropped due to excessive bumping, and there is no risk that fuel used for electrical generation will be insufficient (at this point, residual fuel used to maintain temperature is reduced). Hence in the present embodiment when generated current is at or below 3 A, no control to respond to bumping is executed. Thus in a state whereby the system does not experience fuel shortages, performing a control for bumping enables the prevention of destabilization of the fuel cell module **2** state, excessive temperature drops, and the like.

Next, in step S**2** of FIG. **12**, a determination is made by bumping determination circuit **110***a* (FIG. **6**) as to whether excessive bumping is occurring in the vaporizing section **20***a* of reformer **20**; if excessive bumping is occurring, the system advances to step S**3**; if it is not occurring, the system advances to step S**4**. Specifically, control section **110**, which is a controller, controls fuel flow regulator unit **38**, which is a fuel supply device, so that target fuel supply amount Ft, set in accordance with required generated power, is supplied to reformer **20**. The fuel amount Fa actually sent by fuel flow regulator unit **38** to reformer **20** is measured by fuel flow volume sensor **132**, a fuel supply amount detection circuit (FIG. **6**). If a state continues for a predetermined time or greater in which the amount of fuel Fa actually supplied declines by a predetermined amount or more relative to the target fuel supply amount Ft, it is determined that excessive bumping is occurring inside vaporizing section **20***a*. In the present embodiment, if there is a 70% or greater drop in supplied fuel amount Fa relative to the target fuel supply amount Ft, i.e., if the state whereby (Fa/Ft)≤0.3 continues for 3 seconds or more, a determination is made that excessive bumping is occurring.

FIG. **3** is a time chart showing an example of the control results for a control on bumping; the topmost graph shows fuel cell module **2** generated current, the second graph shows fuel cell module **2** output voltage, and the last graph shows actually supplied fuel amount Fa with a solid line and target fuel supply amount Ft with a dotted line. In the FIG. **13** example, at time t**100** the actually supplied fuel supply amount Fa has dropped by 70% or more relative to target fuel supply amount Ft, and at time t**101** three seconds after time t**100** a determination is made by bumping determination circuit **110***a* that excessive bumping has occurred.

Next, at step S**3** in FIG. **12**, extracted power limiting circuit **110***b*, which is built into control section **110** (FIG. **6**), limits current extracted from fuel cell module **2** to inverter **54** as a bumping response control. In the example shown in FIG. **13**, when a determination is made at time t**101** that excessive bumping has occurred, extracted power limiting circuit **110***b* reduces generated current by 50% and limits the extraction of power.

In the conventional solid oxide fuel cell shown in FIG. **15**, the fuel cell module output voltage drops after excessive bumping has occurred. This is because the actual fuel supply amount declines by more than the target fuel supply amount due to the occurrence of excessive bumping, and if the electrical generating capacity of the fuel cell stack has declined, the same current is extracted from the fuel cell module as before the occurrence of bumping. Voltage drops of this type place a burden on each of the fuel cell units constituting the fuel cell stack, and cause the degradation of each fuel cell unit to advance. By contrast, in FIG. **13** of the present embodiment after it is determined that excessive bumping has occurred at time t**101**, extraction of power is limited by reducing the current extracted from fuel cell module **2**, so that a drop in output voltage is avoided. Note that in the present embodiment after the actually supplied fuel amount Fa has begun to drop, the system limits extracted power after waiting to determine if this state continues for 3 seconds, but a decline in fuel cell module **2** output voltage can be avoided. Here, fuel flowing out from reformer **20** passes through fuel gas supply pipe **64** and manifold **66**, which is a dispersion chamber, and reaches each of the individual fuel cell units **16**. Therefore after the actual fuel supply amount introduced into reformer **20** begins to decline, the effect thereof extends to each of the individual fuel cell units **16**, and there is a time lag of approximately 5 seconds until voltage begins to drop. Therefore voltage drops can be avoided even after a determination is made of whether a drop in fuel supply amount has continued for a predetermined time. In the example shown in FIG. **13**, because extraction of more power than the amount of the decline in generated power caused by the decline in the actual fuel supply amount is suppressed, the fuel cell module **2** output voltage conversely rises.

With respect to limiting the extraction of power by extracted power limiting circuit **110***b*, it is preferable to maintain extraction of a predetermined amount of power or greater while reducing to 50% or less the power extracted from fuel cell module **2**. This is because even if excessive bumping is occurring, the amount of fuel actually supplied does not decline to zero, and supply of a certain amount of fuel continues. Therefore if extraction of power from fuel cell module **2** is completely stopped, the problem arises that not only does excess fuel not contributing to electrical generation increase, but the temperature inside fuel cell module **2** rises excessively due to the combustion of large amounts of surplus fuel. To avoid such problems, if there is a determination that excessive bumping has occurred, it is preferable to maintain the extraction of power even as extracted power is being greatly reduced. However, depending on the scale of bumping estimated to occur inside the reformer, and on conditions such as fuel cell module heat

insulation characteristics, it is also possible to completely stop the extraction of power as part of the limitation of power extraction.

The limiting of power extraction begun in step S3 of FIG. 12 is continued for approximately 2 seconds in step S6 which follows. Next, in step S7, the bumping control for limiting power extraction ends, and one iteration of the processing shown in FIG. 12 is completed. In the example shown in FIG. 13, limitation of power extraction ends at time t102. Note that as shown in FIG. 13, in the present embodiment even after the limiting of power extraction at time t102 ends, the amount of power extracted does not instantaneously return to the pre-limiting level; rather the extraction amount is gradually recovered, so that at time t103 it is restored to the pre-limiting level. In the present embodiment, this control is the normal control when increasing the amount of power extracted, and a similar control is executed, for example, when increasing the amount of power extracted in response to an increase in demand power.

In step S2 of FIG. 12, on the other hand, if no determination is made of excessive bumping, the system advances to step S4; at step S4 a judgment is made as to whether the fuel cell module 2 output voltage is at an appropriate value. Specifically, a judgment is made of whether fuel cell module 2 output voltage Va as measured by electrical power state detecting sensor 126, which is an output voltage detection circuit, has dropped by a predetermined amount or more relative to target output voltage Vt. In the present embodiment the judgment of whether output voltage Va is 30% or more below target output voltage Vt, i.e. whether the voltage has dropped to the point that $(Va/Vt) \leq 0.7$, is made by bumping determination circuit 110*a*. If the voltage has fallen the system advances to step S5; if it has not fallen, one iteration of the processing in flowchart 1 of FIG. 12 is completed.

As described above, if excessive bumping occurs and extraction of power is maintained when the generating capacity of fuel cell stack 14 has dropped, the fuel cell module 2 output voltage declines. Also, output voltage drops as output current increases even if fuel cell module 2 is being operated normally, therefore the optimal output voltage estimated for each output current is pre-set as the target output voltage Vt. In step S4 a determination is made of the proportion of the decline in measured output voltage Va relative to the target output voltage Vt estimated in this way for each output current. If output voltage Va has dropped greatly relative to estimated target output voltage Vt, there is a high possibility that excessive bumping has occurred even if a continuous decline in the amount of fuel Fa actually supplied is not observed, so bumping determination circuit 110*a* judges that excessive bumping has occurred.

When a judgment is made that excessive bumping has occurred, the current extracted from fuel cell module 2 to inverter 54 is reduced 70% by extracted power limiting circuit 110*b* in step S5 as a control against bumping. I.e., the current extracted from fuel cell module 2 is limited to 30% of the value prior to limiting power extraction. The limiting of power extraction started in step S5 of FIG. 12 is continued for approximately 2 seconds in step S6 which follows. Next, in step S7, bumping control to limit power extraction ends, and one iteration of the processing shown in FIG. 12 is completed.

Note that in step S2, when a continuous decline in fuel supply amount Fa is observed, the current extracted from fuel cell module 2 is reduced by 50%, whereas when a determination is made in step S5 of a decline in output voltage, extracted current is reduced by a larger 70%. Thus there is much greater limiting when power extraction is limited based on a decline in output voltage than when limiting is based on a continuous decline in fuel supply amount Fa. This is done in order to more reliably protect each of the individual fuel cell units 16 by more greatly reducing the amount of electrical generation, because when fuel cell module 2 output voltage is beginning to drop, fuel shortages in each of the individual fuel cell units 16 have already started.

Also, even when no determination of a continuous drop in fuel supply amount Fa is made, a determination that excessive bumping has occurred is made using the decline in output voltage as a backup, so that even when a continuous decline in fuel supply amount Fa cannot be detected, the negative effects of an excessive bumping occurrence can be suppressed. When a decline in output voltage is detected, limits on the extraction of power are immediately started, therefore even after the detection of a voltage drop, the negative effects on each of the individual fuel cell units 16 can be kept to a minimum.

Using the solid oxide fuel cell 1 of the present embodiment of the invention, the power extracted from fuel cell module 2 is limited (FIG. 12, steps S3, S5) by extracted power limiting circuit 110*b* when a determination of excessive bumping in water within vaporizing section 20*a* is made by bumping determination circuit 110*a*. Extraction of power in excess of generating capacity from a fuel cell stack 14 in which generated capacity has declined due to the effects of bumping inside vaporizing section 20*a* is thus suppressed, therefore degradation of fuel cell stack 14 is suppressed, and the number of lifespan years can be dramatically improved.

Also, using solid oxide fuel cell 1 of the present embodiment, the placement of manifold 66 (FIG. 2) results in a time lag before the effects of the fuel reduction reach each of the individual fuel cell units 16. Therefore bumping determination circuit 110*a* determines the occurrence of excessive bumping after identifying whether the decline in fuel supply amount has continued for a predetermined time (FIG. 12, step S2), and even when power has been limited, the negative effects on each of the individual fuel cell units 16 can be fully suppressed. The occurrence of excessive bumping can thus be accurately determined, and the operation of fuel cell module 2 can be prevented from becoming unstable due to repeated unnecessary limitations of power caused by false determinations.

Furthermore, excessive bumping of water caused by output voltage drops can be determined (FIG. 12, step S4) using the solid oxide fuel cell 1 of the present embodiment, therefore even when excessive bumping cannot be detected by determinations based on fuel supply amount (FIG. 12, step S2), control against bumping can be reliably executed. In addition, because "fuel depletion" or "fuel shortages" based on excessive bumping of water continue for a certain period of time (FIG. 15), negative effects on fuel cell stack 14 can be sufficiently reduced even when there has been a response to bumping following a drop in output voltage.

Also, using the solid oxide fuel cell 1 of the present embodiment, extraction of power at or above a predetermined amount is maintained even when power is limited (FIG. 12, steps S3, S5), therefore excess temperature rises of fuel cell module 2 caused by increases in surplus fuel can be prevented while avoiding "fuel depletions" or "fuel shortages" in fuel cell stack 14.

Moreover, using solid oxide fuel cell 1 of the present embodiment, extracted power limiting circuit 110*b* does not execute power limiting when the current generated by fuel

cell module **2** is at or below a predetermined amount (FIG. **12**, step S**1**). Therefore in the region in which generated power (current) is at or below a predetermined amount, where it is clear that "fuel depletions" or "fuel shortages" caused by excessive bumping do not occur, unnecessary power limits can be avoided by a simple control.

Above we have described a preferred embodiment of the present invention, but various changes may be added to the above-described embodiments.

Also, in the above-described embodiment, when generated current is 3 A or below, bumping control is not implemented (FIG. **12**, step S**1**), but as a variant example it is possible to change the limiting of power extracted from fuel cell module **2** in response to generated current or generated power. For example, the present invention can be constituted so that in a state where the power generated by fuel cell module **2** is large, the power extracted from fuel cell module **2** is limited much more (extracted power reduced) than when generated power is small.

In the present variant example, when generated power is large, power is limited much more than when generated power is small, therefore unnecessary limiting of power can be prevented when power is small, while reliably avoiding "fuel depletions" or "fuel shortages" during larger power output, when fuel utilization rate is high.

What is claimed is:

1. A solid oxide fuel cell system for generating electrical power using reformed fuel reformed by adding steam to supplied fuel, comprising:

a fuel cell module including a plurality of fuel cell units;

a fuel supply device configured to supply fuel;

a reforming chamber configured to react the fuel supplied from the fuel supply device with steam to reform the supplied fuel and supply the reformed fuel to the fuel cell module;

a vaporization chamber disposed on the upstream side of the reforming chamber and configured to generate the steam therein and supply the generated steam to the reforming chamber;

a water supply device configured to supply water to the vaporization chamber for vaporization of the water to generate the steam;

a controller programmed to control the fuel supply device and the water supply device, and to control extraction of electric power from the fuel cell module, wherein the controller includes a bumping determination circuit and an extracted power limiting circuit,

wherein the bumping determination circuit is programmed to determine an occurrence of excessive and sudden vaporization of water in the vaporization chamber, and

wherein the extracted power limiting circuit is programmed to reduce extraction of the electrical power from the fuel cell module when the bumping determination circuit determines an occurrence of excessive and sudden vaporization of water in the vaporization chamber.

2. The solid oxide fuel cell system of claim **1**, further comprising (i) a fuel supply amount detection circuit operable to detect an amount of the fuel supply into the reforming chamber and (ii) a dispersion chamber configured to accumulate the reformed fuel therein and distribute the reformed fuel to each of the fuel cell units,

wherein the bumping determination circuit is programmed to determine an occurrence of excessive and sudden vaporization of water in the vaporization chamber when the fuel supply amount detection circuit detects that a decrease of the amount of fuel supply below a target amount of fuel supply by a predetermined amount or more continues for a predetermined time duration or more.

3. The solid oxide fuel cell system of claim **2**, further comprising an output voltage detection circuit operable to detect an output voltage of the fuel cell module,

wherein the bumping determination circuit is programmed to determine an occurrence of excessive and sudden vaporization of water in the vaporization chamber when the output voltage detection circuit detects a decrease of the output voltage below a target output voltage by a predetermined voltage or more.

4. The solid oxide fuel cell system of claim **3**, wherein the extracted power limiting circuit is programmed to reduce extraction of the electrical power from the fuel cell module to a predetermined electrical power which is not zero.

5. The solid oxide fuel cell system of claim **1**, wherein the extracted power limiting circuit is programmed to reduce extraction of the power from the fuel cell module to a larger degree when the power generated by the fuel cell module is at a first level than when generated power is at a second level which is lower than the first level.

6. The solid oxide fuel cell system of claim **5**, wherein only under a condition that electricity generated by the fuel cell module is above a predetermined amount, the extracted power limiting circuit is operable to reduce extraction of electrical power from the fuel cell module when the bumping determination circuit determines an occurrence of excessive and sudden vaporization of water in the vaporization chamber.

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